Lessons Learned From Developing Advanced Space Power Systems Applied to the Implementation of DC Terrestrial Micro-Grids

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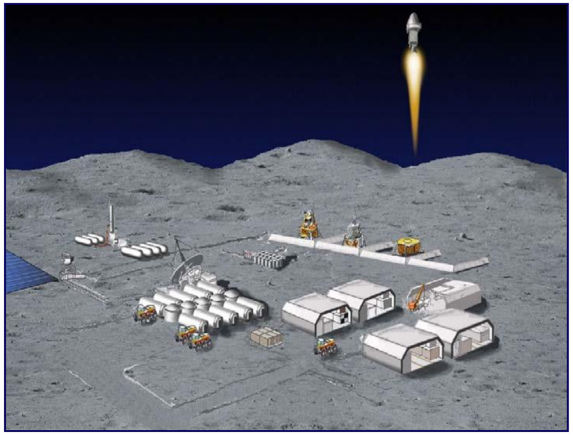
Discussion Topics

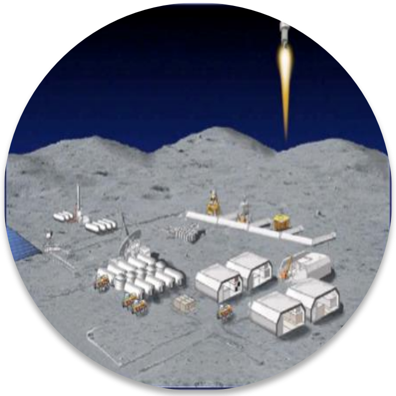
- Why is NASA interested in Smart Grid?
- Advanced Terrestrial Smart Grids
- ISS Description
- DC Power Challenges
  - Fault Control
  - Stability
- Wrap-up

Why Intelligent Power / Smart Grid?

- **NASA**
  - **Provide a utility–like power generation and distribution capability with automated operation to enable deep space exploration and settlement**
- **Terrestrial**
  - **Increase the power delivery capability and reliability of the grid by integrating renewables and energy storage without major increases to the transmission and generation infrastructure**



Power Grid Challenges



Exploration Power vs Terrestrial Power

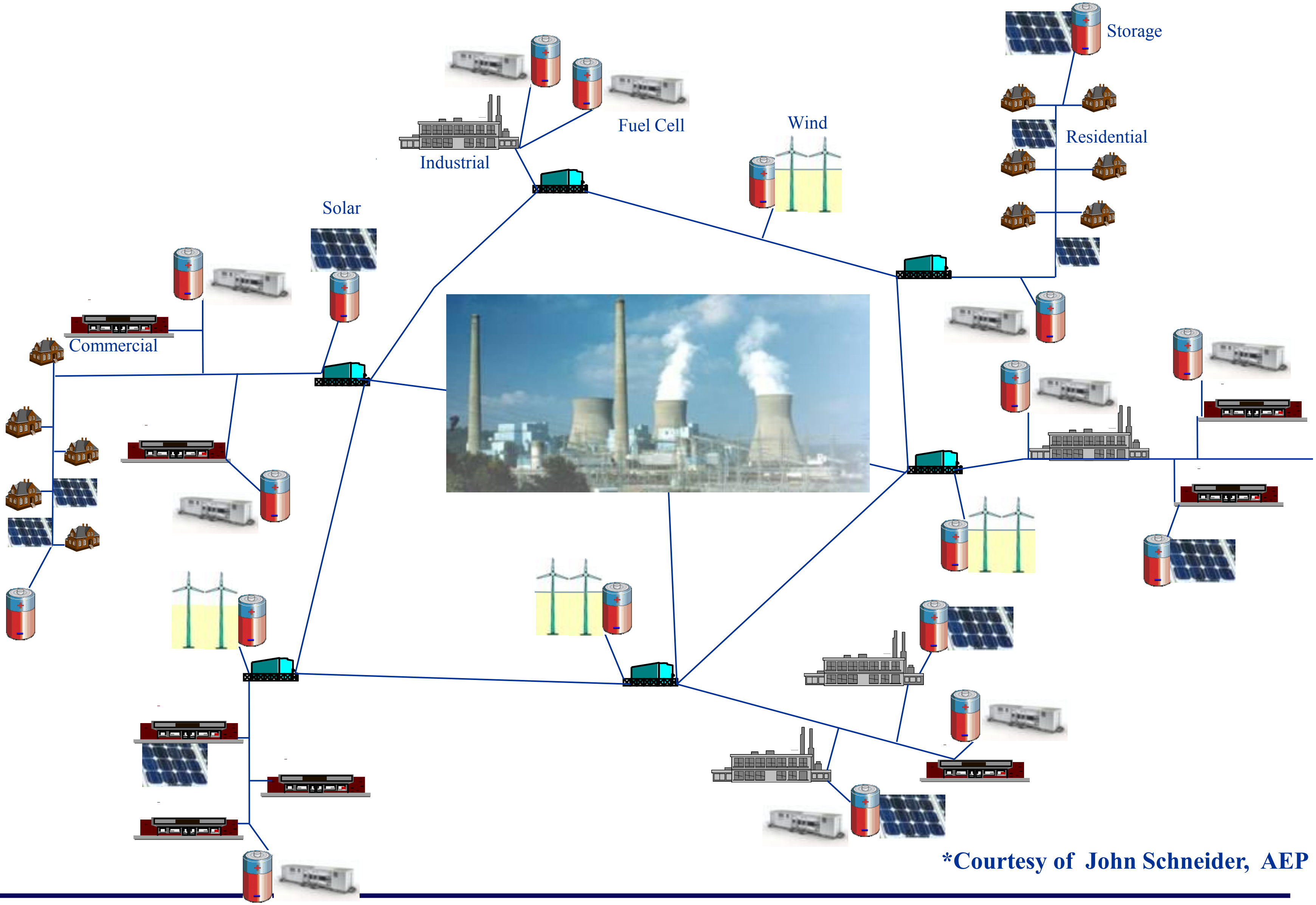
Exploration Power | ***Terrestrial Power***

X	Increased power demands	X
X	Utilization of diverse power sources (renewables)	X
X	Incorporation of large amounts of distributed energy storage	X
X	Seamless accommodation of Variable / Peak load demand	X
X	Failure diagnostics and prognostics for power components	X
X	Automated control for operations management, fault detection and system reconfiguration	X
X	Long term reliability / availability for exploration survivability and terrestrial users	X

Commonality of Challenges for Grid Developers

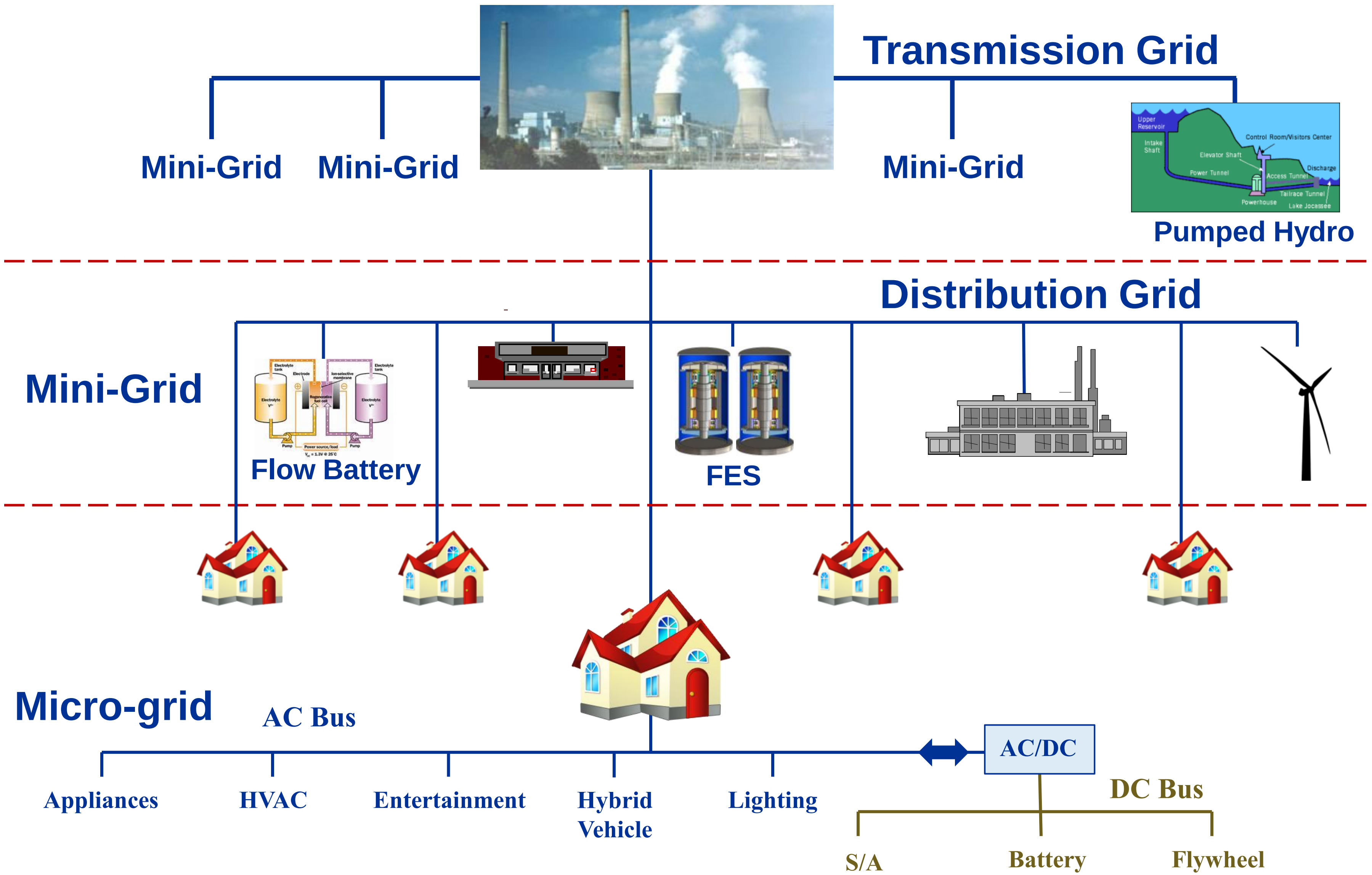
Advanced Terrestrial Smart Grids

…the Grid of the Future?*

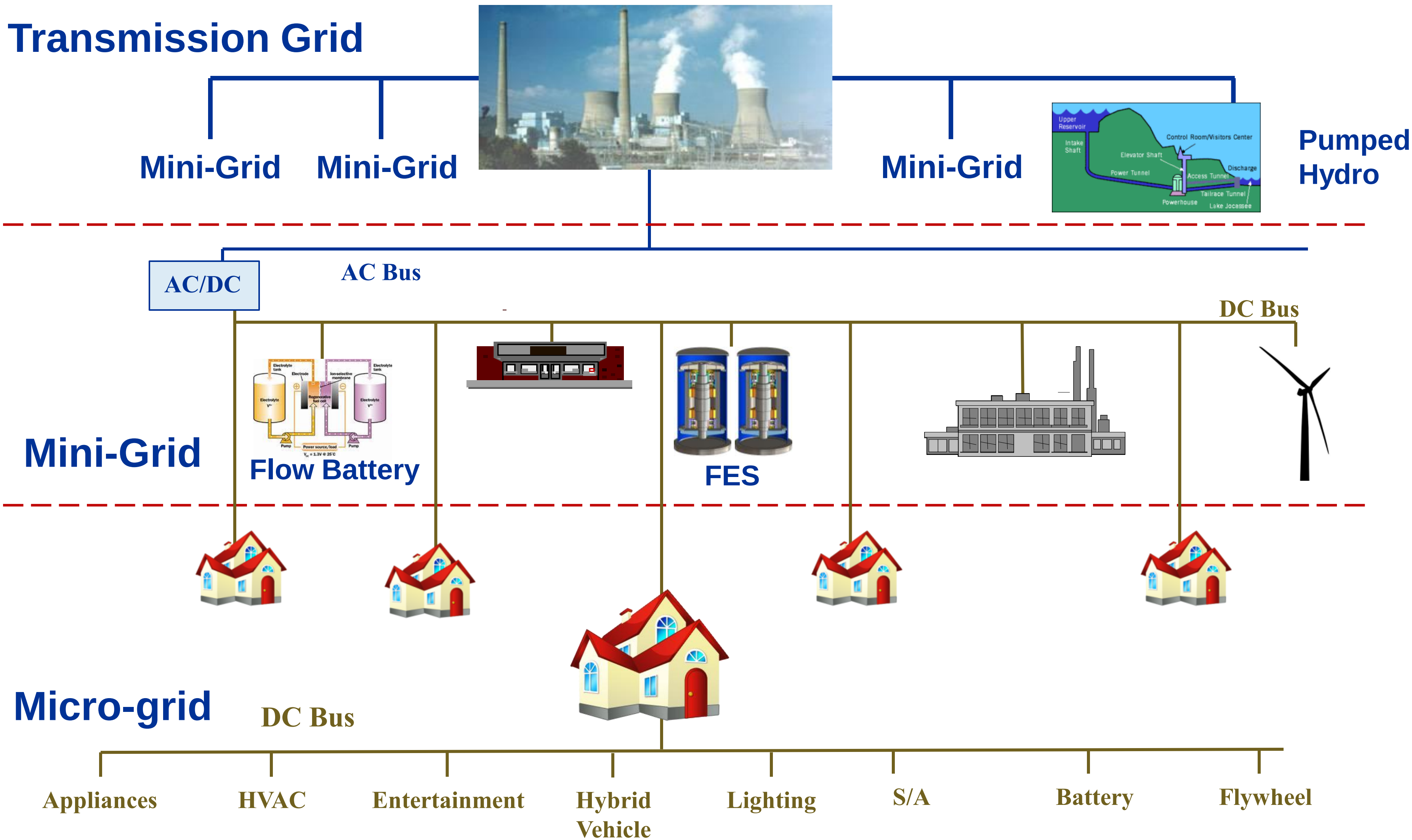


*Courtesy of John Schneider, AEP

Advanced Power Grid Hierarchy



More Advanced Power Grid Hierarchy



Why DC Micro grids?

- DC powered electrical devices make up 50 to 80%* of the load in many buildings
  - Computing equipment
  - LED lighting will become more common
- Variable speed drives are penetrating into the appliance market.
- Many renewables such as solar / wind / batteries (flow and non-flow) fuel cells flywheels etc. are already compatible with DC systems (Have DC outputs)

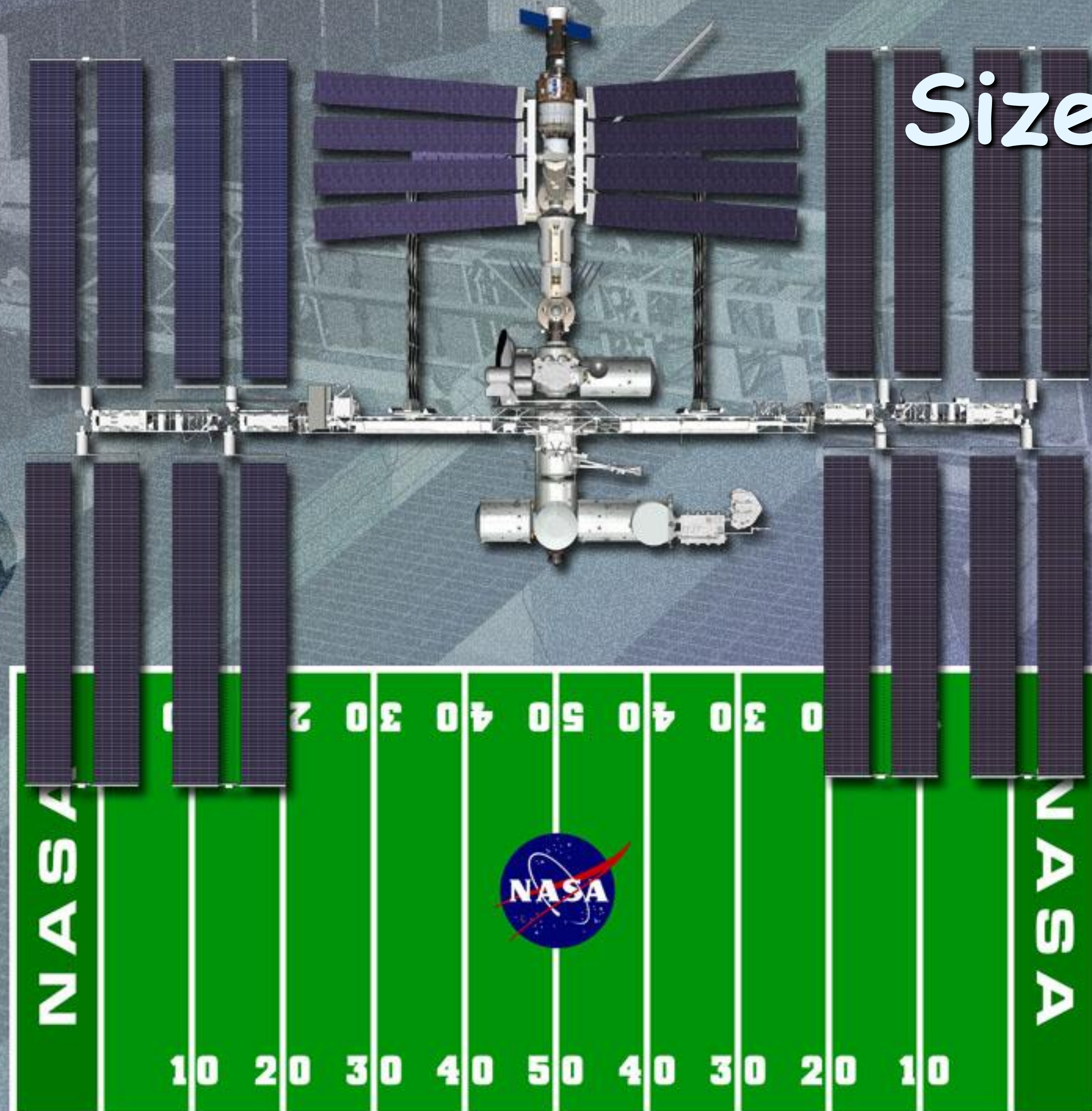
* Nextek Power Systems

DC Distribution and the International Space Station

Size

Width: 108 meters
Length: 80 meters

Weight:
456,279 kilograms

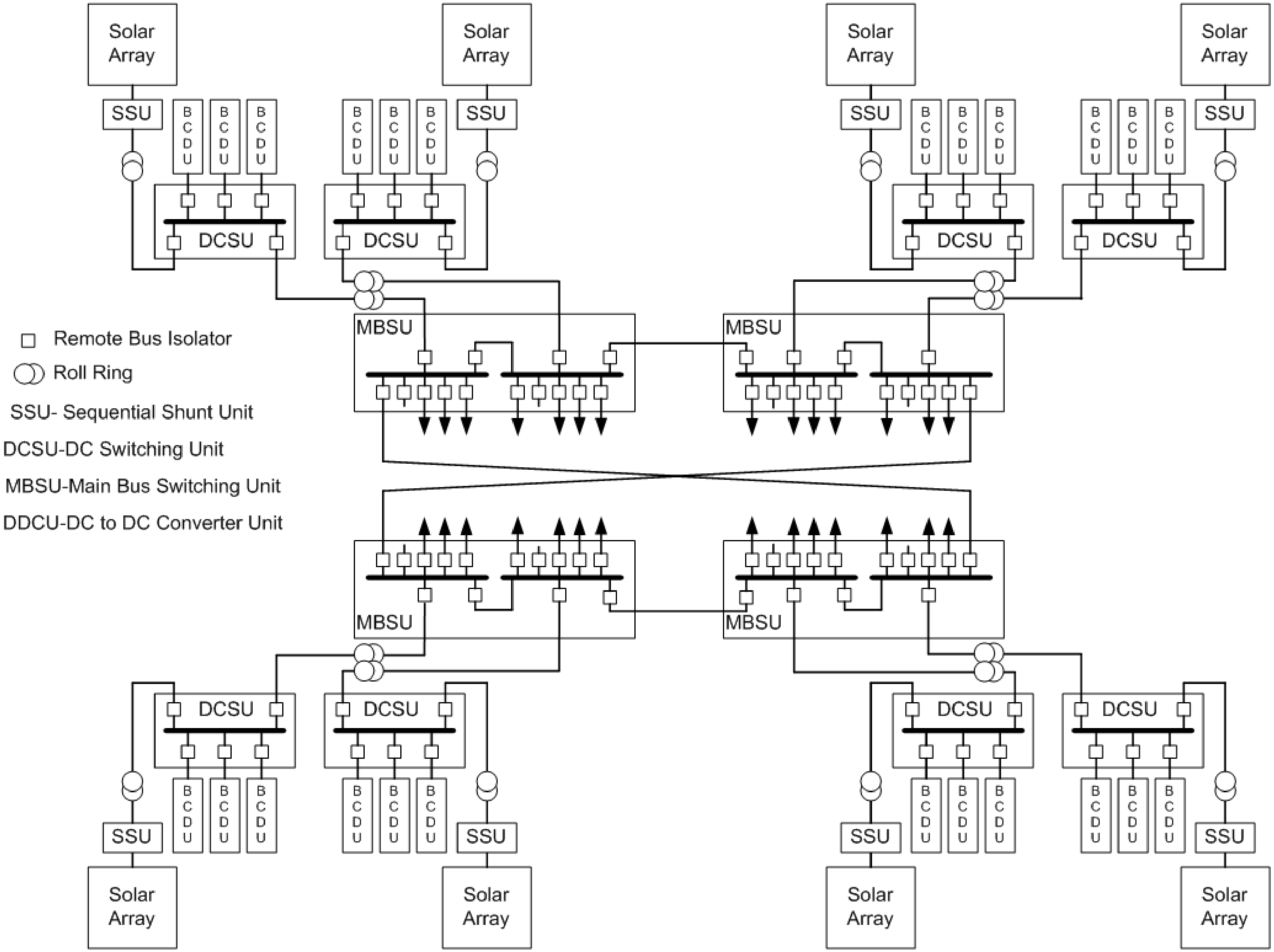


International Space Station

Power System Characteristics

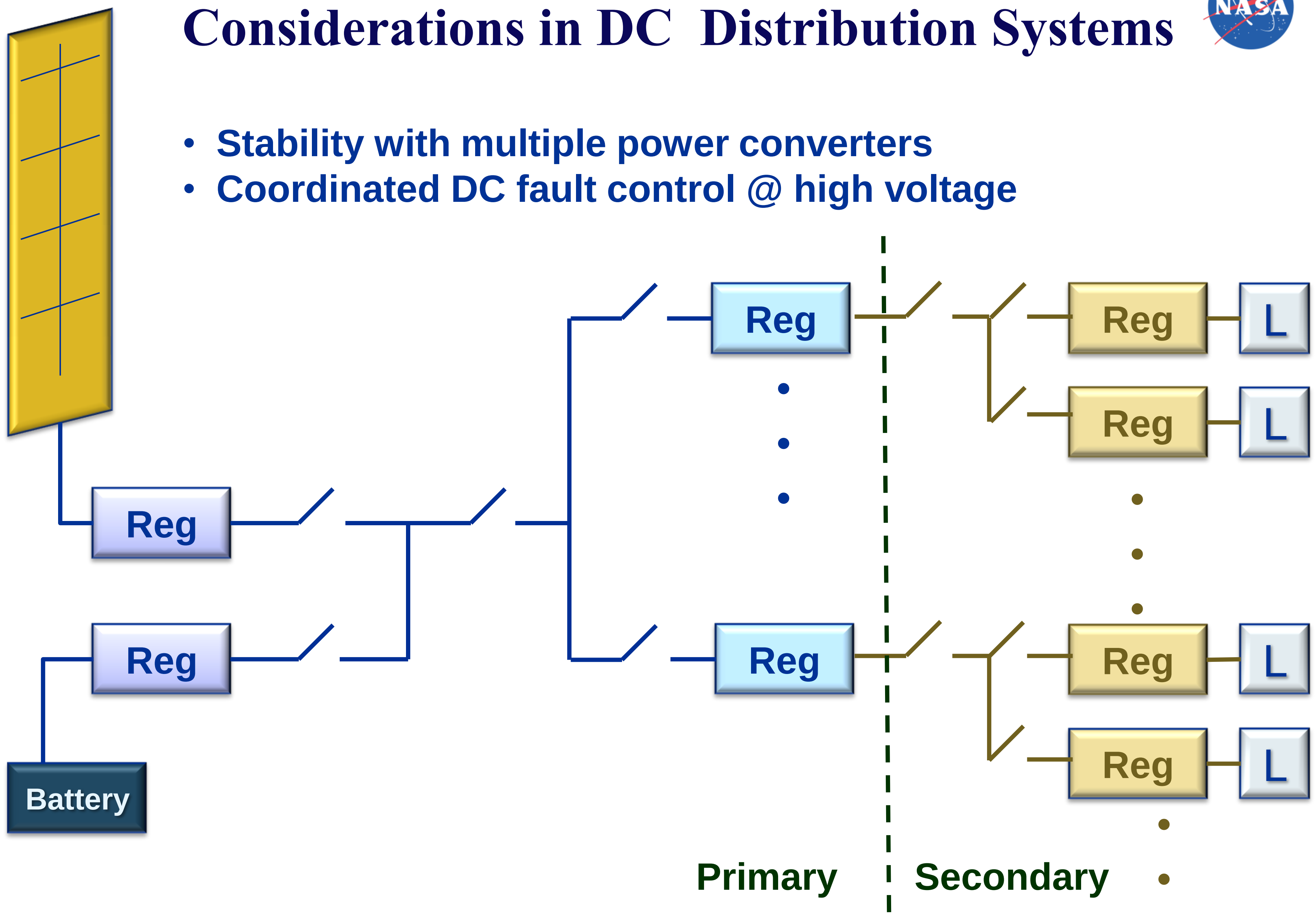
- Power 75 kW average
- Eight independent power channels -- 9.75 kW
- Solar array power 200+ kW
  - Planar silicon arrays
  - 18% Efficient
- NiH battery storage – 3 per channel (2 ORUs)
  - 76 cells @ 81 amp*hrs / battery
- Distribution
  - 116 - 170 V primary
  - 120 V secondary
- Contingency power > 1 orbit
- System lifetime of 15+ years

ISS Primary Grid



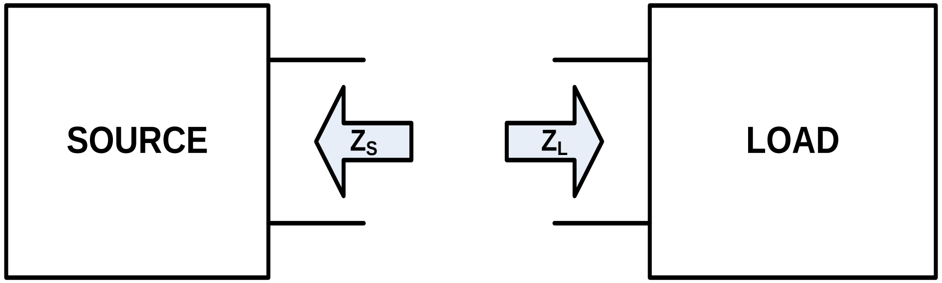
Considerations in DC Distribution Systems

- Stability with multiple power converters
- Coordinated DC fault control @ high voltage



Stability

Power System Stability



- If $|Z_S| < |Z_L|$ for all frequencies, then the system is stable

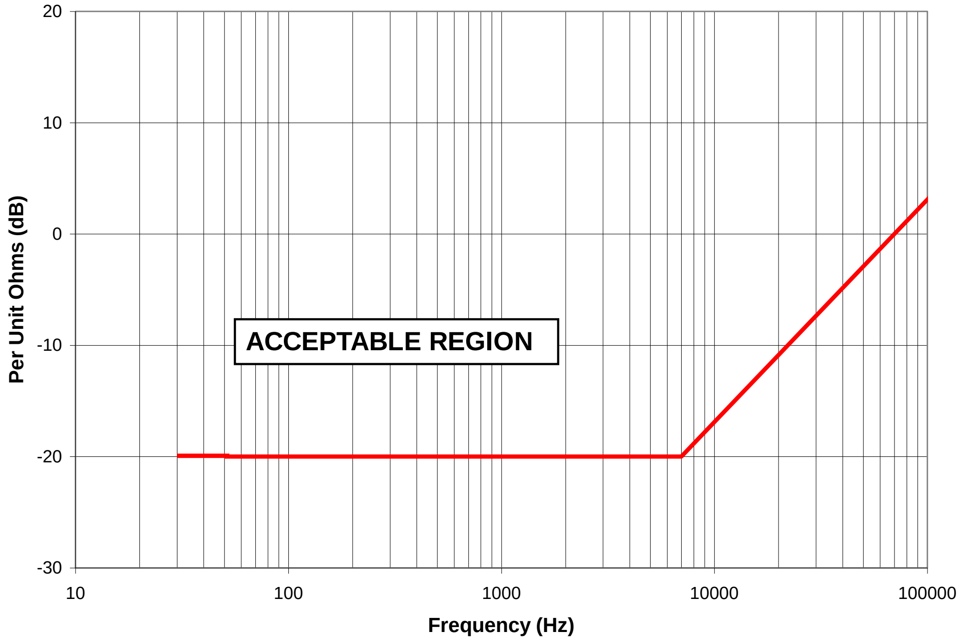
- When $|Z_S| > |Z_L|$, further analysis is needed to determine system stability.

$$Z = \frac{Z_S \cdot Z_L}{Z_S + Z_L} = \frac{Z_S}{\frac{Z_S}{Z_L} + 1}$$

From SAE Spec AS5698

Power System Stability

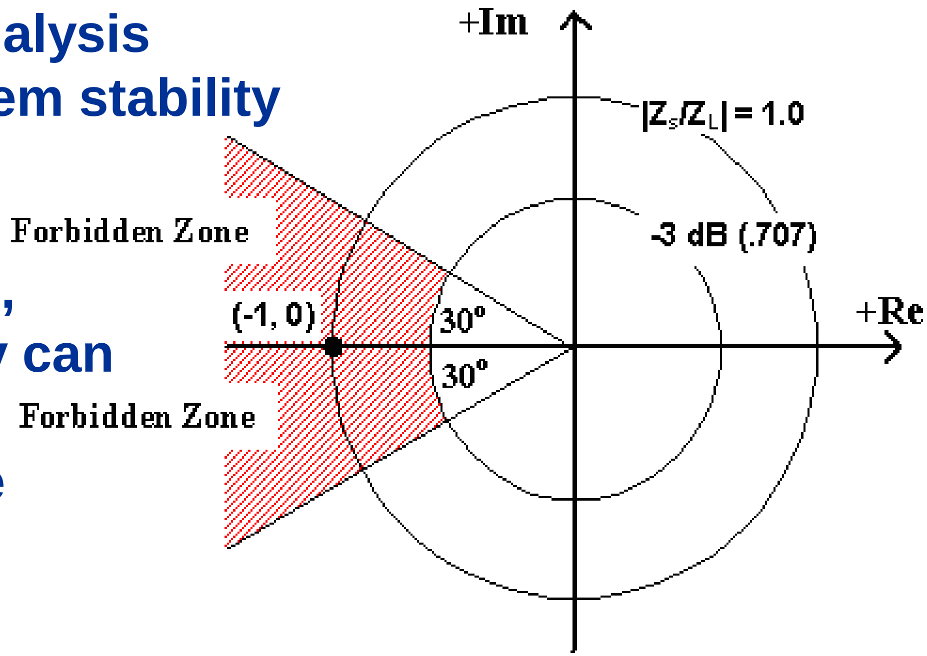
- If $|Z_S| < |Z_L|$ for all frequencies, then the system is stable



Normalized load Input Impedance Limit

Power System Stability

- When $|Z_S| > |Z_L|$, further analysis is needed to determine system stability

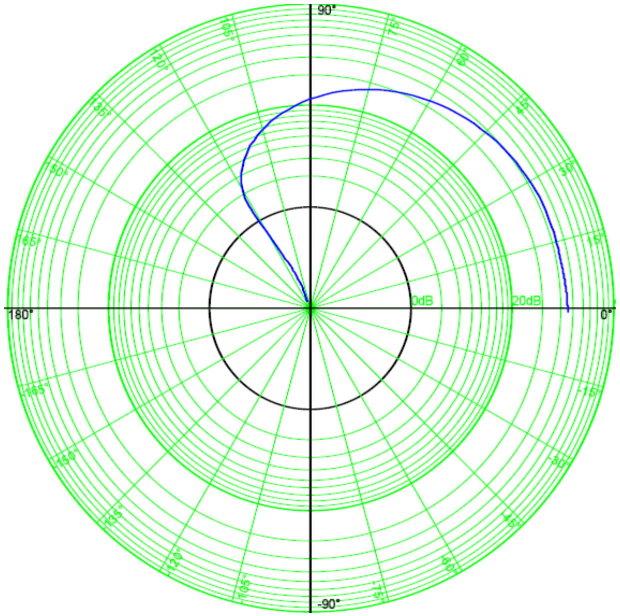


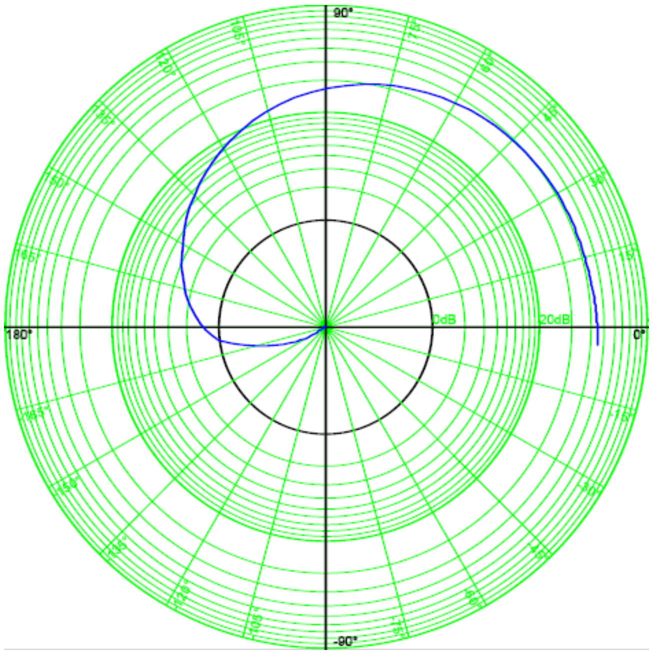
- Using the Nyquist criterion, small-signal system stability can be determined by whether the curve of Z_S/Z_L circles the (-1,0) in the S-plane

- The forbidden region on this diagram establishes a system stability margin.

From SAE Spec AS5698

Power System Stability Examples





Stable System

Under damped but stable system

Stability

- **With soft sources it is generally impractical to avoid crossover of source and load impedances**
  - **Stability is generally determined by phase margin**
- **Loads should have 3 db Ohms of gain margin, or 30 degrees of phase Margin with respect to source impedance**
- **Limit cycles must be avoided when applying loads to current limited sources and resettable protective devices**
- **Phase Margin is 180 degrees minus phase**

DC Fault Control

DC Fault Control

- **Fault Clearing for DC systems is inherently difficult because the current never passes through zero.**
- **Challenges**
  - **Clear the fault quickly with minimum stress on the system**
  - **Minimize the effect on other branches of the system**
- **Coordinated fault response**
  - **Switch closest to the fault needs to trip first**
- **Form factor should be compact and lightweight**

DC Switchgear

	Fuse	Mech Relay	Hybrid	CL Solid State
Resettable	N	Y	Y	Y
Mass	B	Worst	Worst	Worse
Losses	B	Better	Better	Worse
Coordination	B	Worse	Better	Best
System Impacts	B	Worst	Better	Best
Complexity	B	Worse	Worst	Worse

Best
Better
Worse
Worst

B – Baseline
Y – Yes

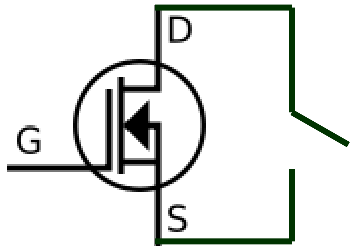
Mechanical Switch: Kilovac Vacuum Relay

Kilovac 500 A Vacuum Switch "Bubba"

Description

- AP350X ***"Bubba"*** -- Largest space-rated switch
- Voltages:
  - 270 Vdc continuous
  - 350 Vdc 10 μsec
- Currents:
  - 500 A continuous
  - <5000 A surge
- Switching time: 10 msec
- Magnetic arc blow-out
- Low loss
- No current limiting
- System transients tend to be high

Hybrid Switch



Schematic of hybrid switch

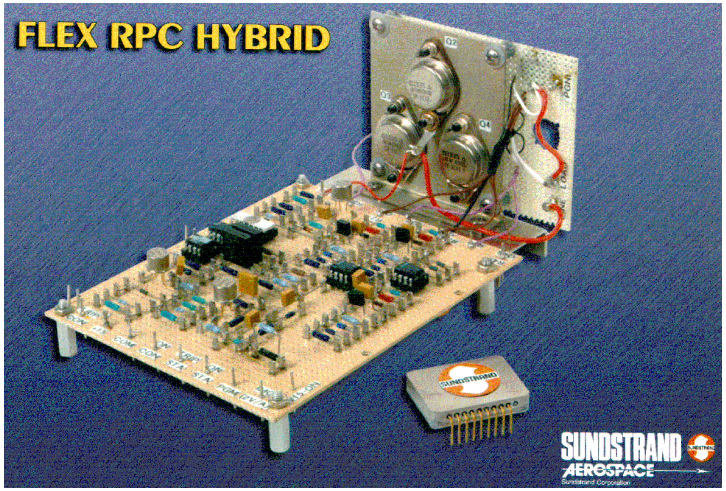
Description

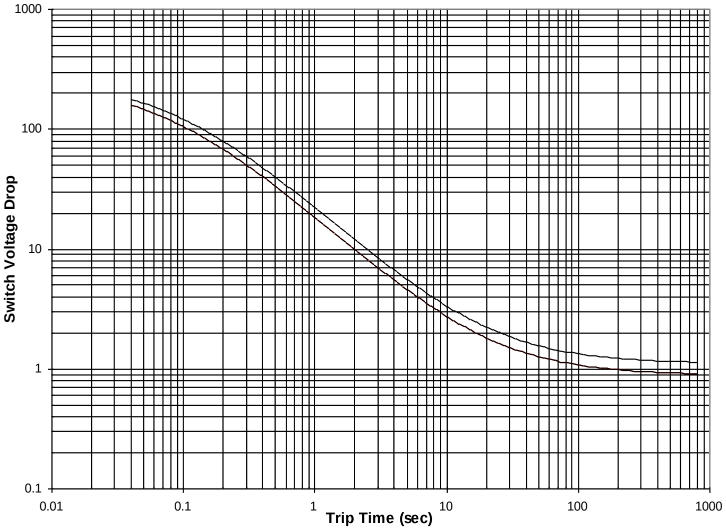
- Contains both mechanical and Solid state components
- Solid state switch permits "soft" turn-on and turn-off
- Mechanical switch provides low loss in on-state
- Mechanical switch does not need to be sized for interrupt
- Trip coordination can be tricky

Current Limited RPC

Description

- Remote Power Controllers control and protect electrical system
- Current limited RPCs provide absolute protection for system wiring
- Can be reset
- Can be paralleled to increase current handling capability
  - Unlike fuses or circuit breakers
- Utilizes an innovative v^2t trip curve.
- Can distinguish between sever and slight overload
- Multi-level trip coordination is easily implemented
  - Avoids ambiguity of using i^2t trip curves

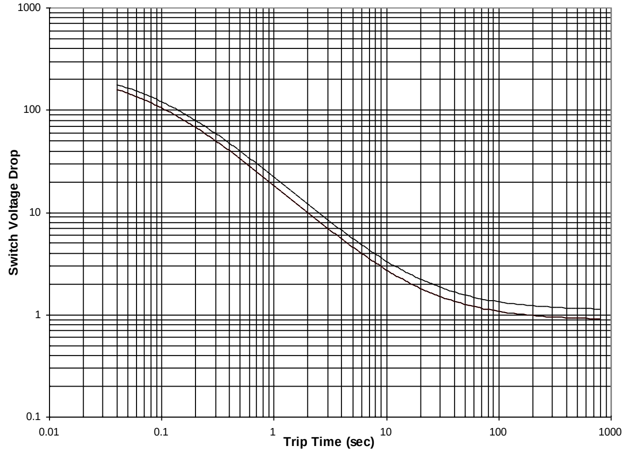


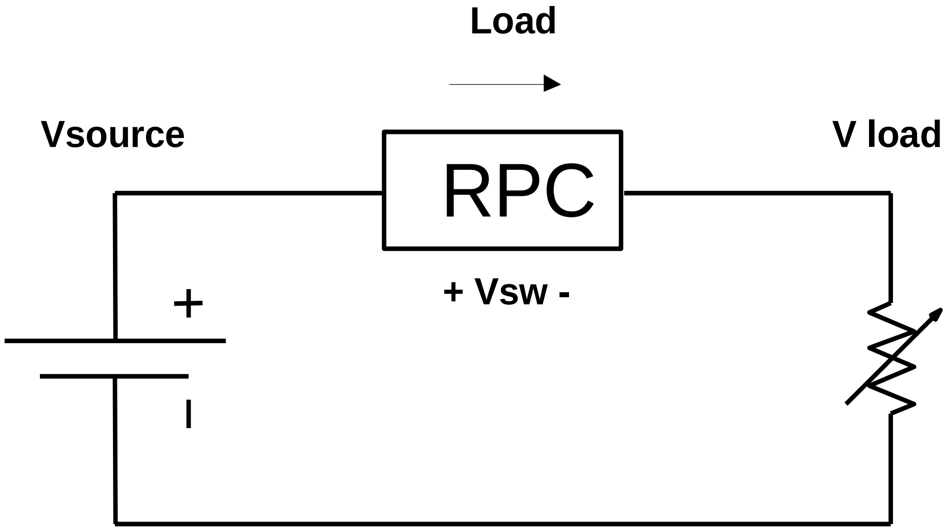


Switch Voltage Drop

Description

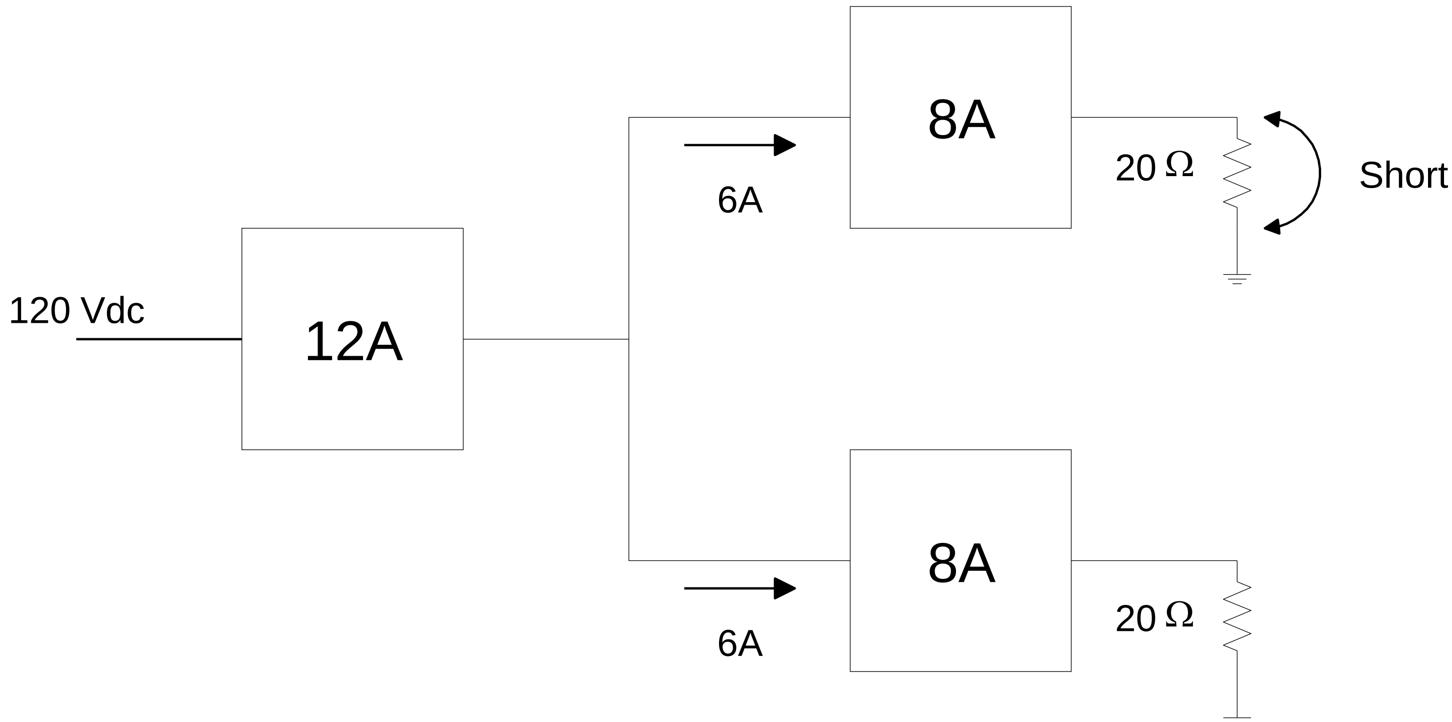
- Utilizes switch voltage drop to determine trip time
- Can distinguish between sever and slight overload
- Trip curve utilizes semiconductor 's safe operating area



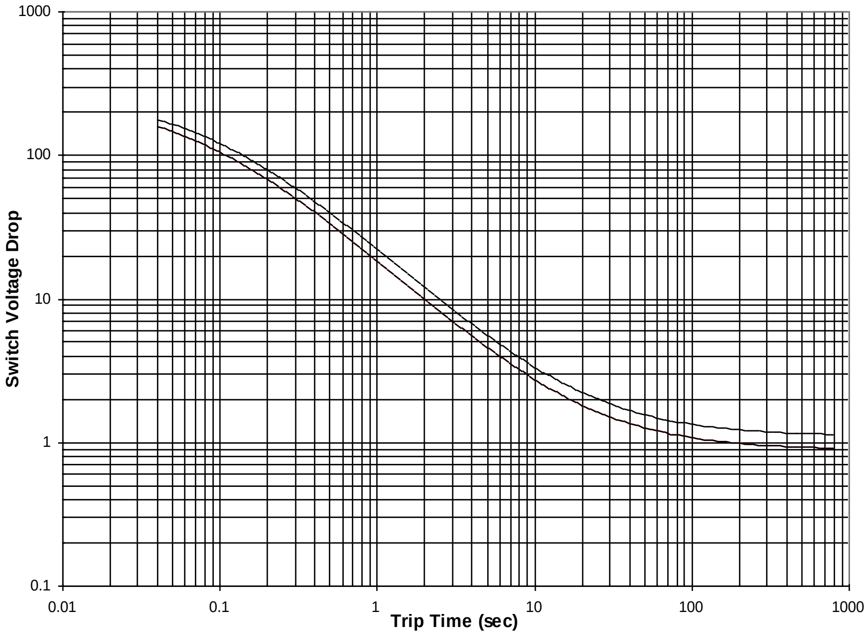


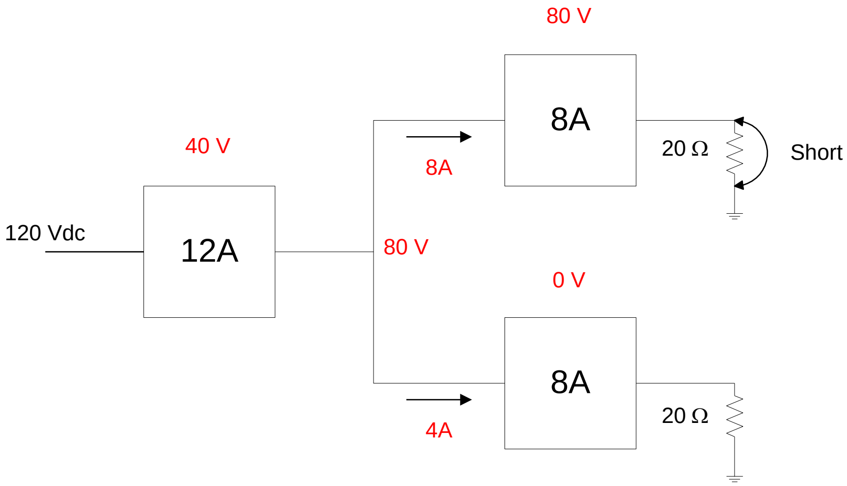
Psw = Load * Vsw

Coordination Example



Coordination Example





Wrap-Up

- **Advanced DC terrestrial micro-grids can learn a great deal from experience developing the International Space Station Power System**
- **The negative impedance of multiple power converters in series can pose stability challenges**
- **Fault control with soft sources such as power converters and solar arrays needs to be accommodated**

References

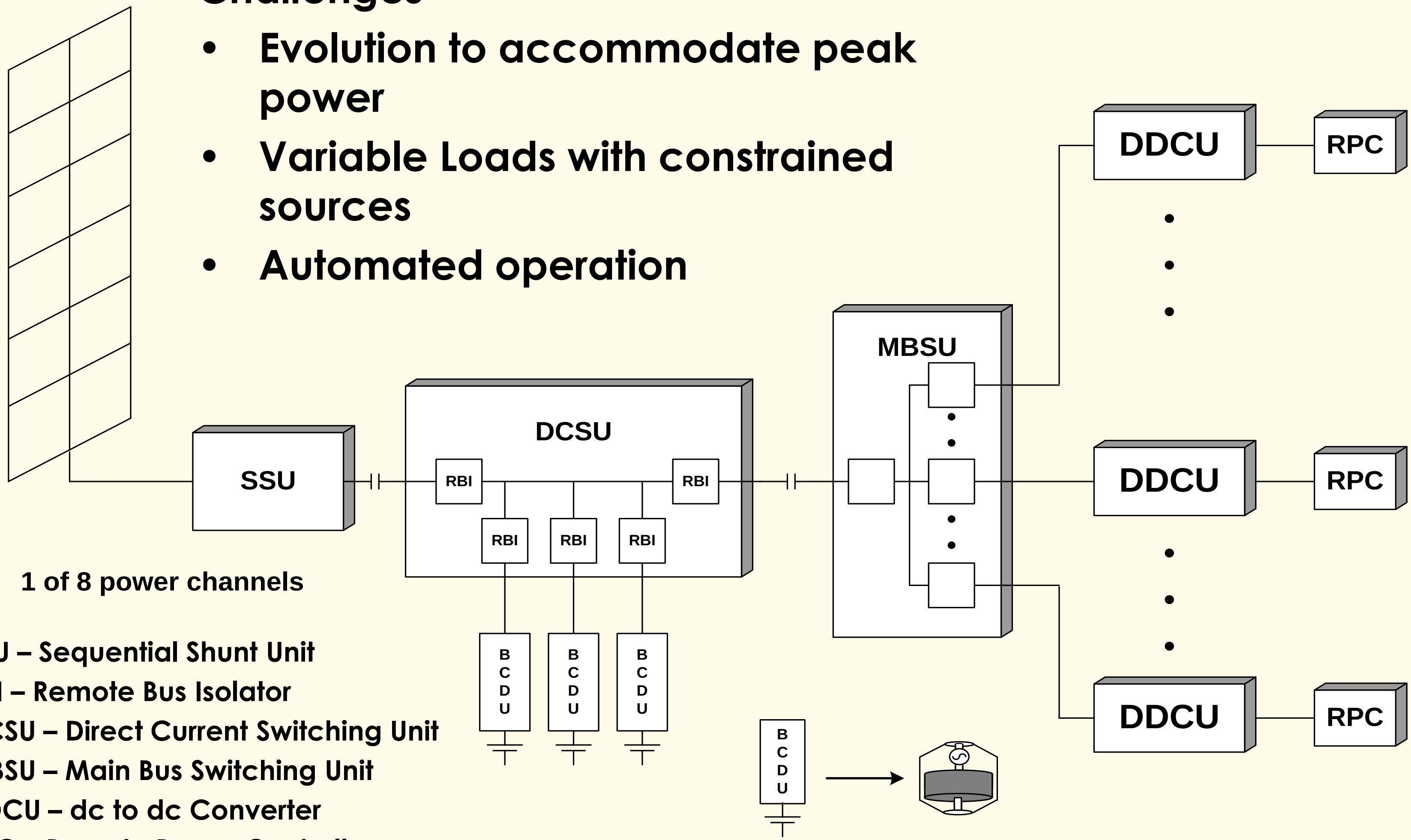
- **David Fox -- Hamilton Sundstrand Corp.**
- **James Soltis – NASA Glenn Research Center**
- **Nextek Corporation**

Back-up

ISS Power Architecture

Challenges

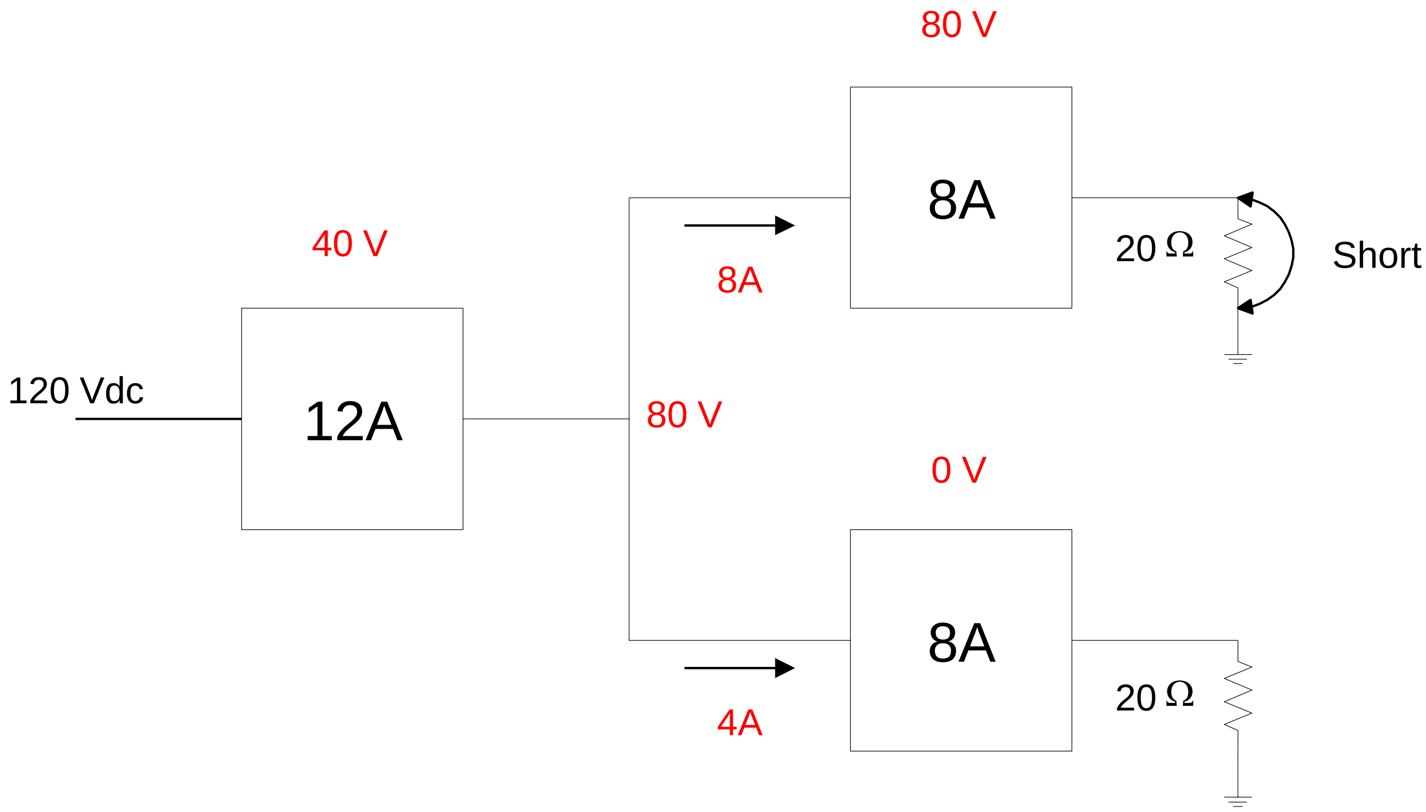
- Evolution to accommodate peak power
- Variable Loads with constrained sources
- Automated operation



1 of 8 power channels

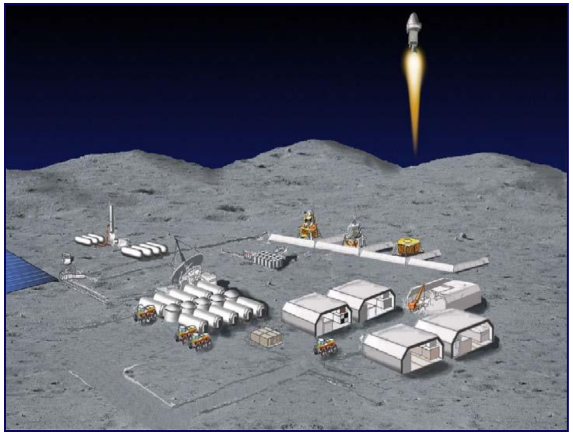
SSU – Sequential Shunt Unit
RBI – Remote Bus Isolator
DCSU – Direct Current Switching Unit
MBSU – Main Bus Switching Unit
DDCU – dc to dc Converter
RPC – Remote Power Controller

Coordination Example



What is NASA's Interest In Smart Grid?

ISS Automation



Planetary Surface Power Systems

Facility Sustainability

Deep Space Habitat

NASA's interest is in the development of technologies that benefit space exploration and enable the Terrestrial Smart Grid